Internship Report

Surface solar radiation at Villeneuve d'Ascq: Climatology and its estimation from satellite

by

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Internship period: 01.02.2018 - 27.06.2018

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Contents

SUMMARY

Solar irradiance at the Earth' surface is determined for physical and biological processes. Solar energy plays an important role as renewable energy alternatives nowadays. This information can help uncover information about the radiation budget at the Earth's surface in detail and the Earth's climatic system in general. Furthermore, the partition between the solar direct and diffuse components is important as it impacts surface processes.

Solar radiation at the surface results from the combined effects of atmospheric gases, aerosols, clouds, and properties. Estimating the global solar radiation by ground measurements has been the first method and it is still being developed and used for monitoring the global radiation. However, since the 90s, using satellite data for estimating the solar radiation has become more common. The interesting advantage is that satellite is capable of covering huge areas while ground measurements give only information at the local scale.

In this work, we analyze the climatology of solar radiation in Villeneuve d'Ascq and we analyze the difference between ground-based and satellite data for different cloud covers. In local scale, ground measurements give reliable data or are used as a reference for evaluating the accuracy of satellite data.

Chapter 1. Introduction

Radiation from the Sun is the primary natural energy source of the Earth. The solar radiation which reaches the top of the atmosphere on a perpendicular plane to the rays, known as solar constant, has an average value of 1360.8 ± 0.5 W/m^2 [1] which varies somewhat depending on the position of the Earth in its elliptical orbit. Under the annual global mean condition, the incident solar radiation at the top of the atmosphere is 341 W/m^2. Of this incident solar radiation, 67 W/m^2 is absorbed during passage through the atmosphere. A total of 102 W/m^2 is reflected back to space: 23 W/m^2 from the surface and 79 W/m^2 from clouds and aerosols and atmosphere. The remaining 161 W/m^2 is absorbed at the Earth's surface [6], so the average transmittance is roughly 54%. These number are very important because the driving energy of atmospheric and ocean dynamics come from the Sun and it's energy's absorption by different components of the Earth's climatic system. For instance, irradiation at the surface is important for photosynthesis which plays an important role in growing of plants. Clouds affect the amount of irradiation at the surface. They reflect roughly 20% of solar energy back to space, thus, they control very much the transmission of solar energy down to the surface. However, the role of clouds in solar transmittance is not very well quantified because cloud covers are very diverse in terms of properties and are complex medium [9] [10].

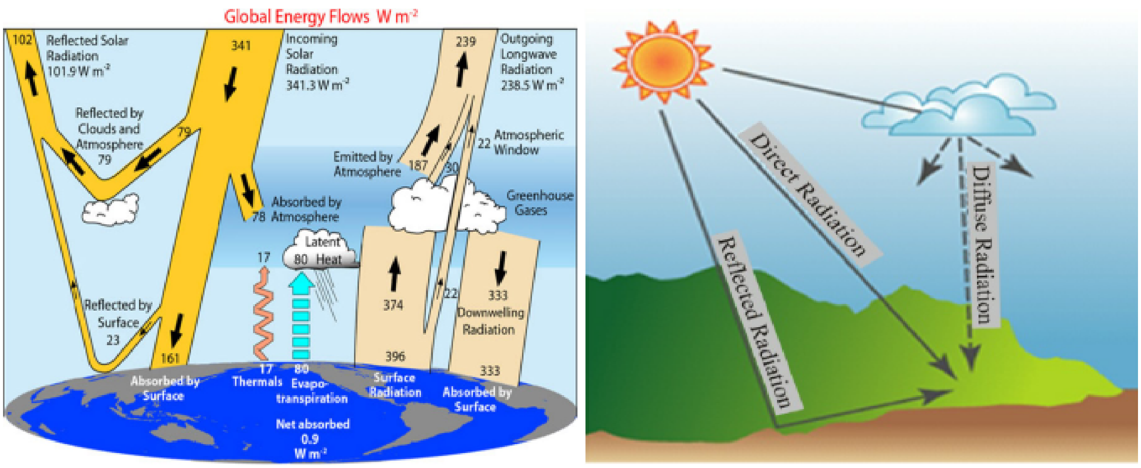


Figure 1: Schematic diagram of the global mean energy balance of the Earth [6]

Nowadays, solar irradiance at the surface plays an important role as its exploitation is renewable energy alternatives as well as its importance in term of understanding Earth's climatic system [2]. In general, the radiation budget at the earth surface is an essential climate variable for climate monitoring and analysis. Solar radiation has been applied for application in various facets of human needs, such as power and water supply for industrial, agricultural and domestic uses. Furthermore, the development the photovoltaic panels has provided another for understanding the variation of incoming solar radiation, since its availability and distribution determine the size of photovoltaic panels needed for a given application or location. The information of global solar radiation is also required for the forecast of the solar heat gain in the building, weather forecast, etc.

The solar radiation received on ground level, known as global radiation is the sum of two components [2]. The first one, named beam or direct radiation, is the fraction of the solar radiation that reaches the ground without being scattered by the atmosphere. The second part is the diffuse solar radiation that reaches the ground after being reflected or scattered by the atmosphere and is considered to arrive from the whole sky dome [2]. Furthermore, the diffuse radiation is important for terrestrial ecosystem productivity [8].

Global solar radiation can be derived by combining observations and modeling studies, which show the combined effects of atmospheric gases, aerosols, clouds, and surfaces. Since the years 90, using satellite data for estimating the solar radiation has been applied for computing the global solar radiation. They are indeed capable of retrieving solar radiation over a large area with an image resolution of a few kilometers. However, these retrievals come possibly some errors due to using some assumption about the content of the atmosphere in gas, aerosols and clouds and their properties. On the other hand, estimating the solar radiation by ground measurements is the most traditional method and they are able to overcome the above disadvantages of satellite and gave an accuracy estimation in local area. Thus, satellite becomes an useful method for retrieving the global radiation or at places where we cannot build an ground measurement such as ocean. In contrast, ground measurement is suitable for estimating solar radiation at local scale.

In this report, we use the data from ground measurements, which were made at Villeneuve d'Ascq, from 2009 to 2016 as a reference. This reference data will be compared with surface solar radiation estimated from satellite instruments (PVGIS – CMSAF approach) [11]. The work is composed of 5 chapters. In the first chapter will be introduced elements of atmospheric radiation and definitions, as well as the instruments used at LOA and the principle of surface irradiance estimate from satellite. Chapter 2 describes elements of the climatology of solar radiation on the surface at Villeneuve d'Ascq as measured by instruments at LOA site. Next, chapter 3 presents climatology of surface solar radiation. Chapter 4 describes the comparison between surface solar irradiance measured in Lille and estimated from satellite measurements using the CMSAF approach. The comparison will be separated in monthly, daily and hourly data and the focus will be on the understanding of the differences between irradiance actually measured and estimated. Conclusion is the last chapter.

Chapter 2. Element of atmospheric radiation

In this chapter, the components of solar radiation are described. In addition, the relation between direct and diffuse transmittances and clouds optical thickness is also indicated in this chapter. Then we will explained briefly how the total radiation and its components on the surface are measured at the ground and estimated from satellite.

2.1 Direct and diffuse components of the solar radiation

The solar radiation is partitioned into direct and diffuse radiation when it propagates through the atmosphere. The extinction of the direct radiation is governed by a basic principle known as Beer - Bouguer - Lambert law. The direct radiation I is linked to the atmospheric optical thickness τ and the solar radiation at top of atmosphere I_o by the the following equation:

$$\boldsymbol{I = I_o exp\ (-m\tau)}$$

where m is the airmass factor and τ is the atmospheric optical thickness. The airmass will be determined by solar zenith angle θ: $m = 1/\cos(\theta)$. The optical depth controls how much the direct radiation is reduced when it propagates through the atmosphere.

On the other hand, diffuse radiation depends on the source of scattering which can be clouds, particles and gas. In addition, it depends also on the reflectance of the surface. There is no simple law to describe diffuse radiation.

2.2 The relation of transmittance and optical depth

As was mentioned above, the relation of direct transmission and optical depth is based on the Beer-Lambert law. The value of direct transmittance follows the equation:

$$\mathbf{T_{direct}} = I/I_o = \exp(-m\tau)$$

From two-stream theory (Bohren, 1987), where photons are constrained to be scattered in only two direction, forward and backward, the transmittance of a layer T_{bs} with the assumption of a black surface, a non-absorbing and homogeneous medium follows the formula [4]:

$$T_{bs} = \frac{2}{2 + \tau^o}$$

where scaled optical depth : $\tau^o = \tau \times (1\text{-}g)$. As a consequence, the diffuse transmittance of a layer is described as $\mathbf{T_{diffuse}} = T_{bs} - T_{direct}$.

The fig.2 show a typical variation of direct and diffuse transmission with the optical depth. The diffuse transmission rises with increasing optical depth stood at 0 and reaches the peak at $\tau \approx \ln[2/(1-g)]$ where g is the asymmetry parameter, and then decreases gradually with a further increase of τ. In contrast, the direct transmission decreases sharply with increasing optical thickness. The higher value of τ the more difficult direct transmittance is detected.

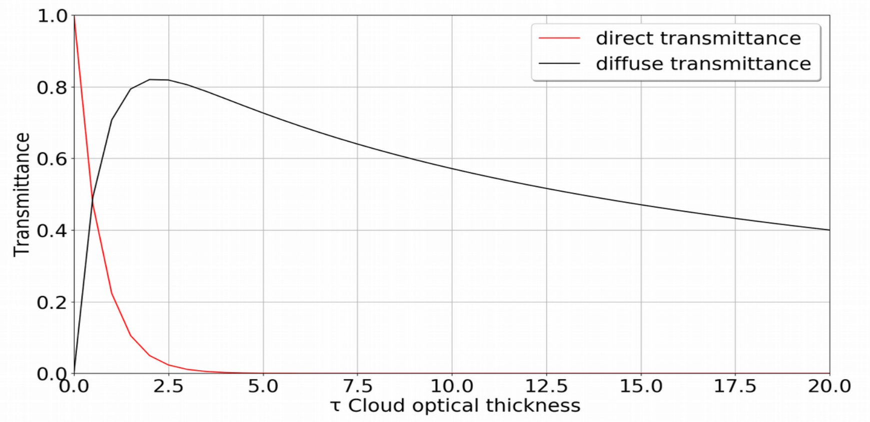


Figure 2: Variation of direct and diffuse transmittance as a function of optical depth

If we consider that the surface is not a black surface, the atmospheric transmittance is described with the following formula [13]:

$$T = \frac{T_{bs}}{1 - \rho R^{o}}$$

where R^o is the reflectance of the atmospheric layer illuminated from below by an isotropic source, and ρ is the surface albedo.

2.3 PVGIS application

PVGIS (Photovoltaic Geographical Information System) is a system which has been developed by the European Commission Joint Research Center, at the JRC site in Ispra, Italy. The aim of PVGIS is to provide solar resource assessment, photovoltaic (PV) performance studies from satellite's measurements [7]. The satellite observations that we chose in this work is PVGIS-CMSAF. The coverage of PVGIS-CMSAF are Europe, Africa and a part of South America at hourly time resolution and a spatial resolution of 2.8 km [11].

In order to retrieving the output of solar radiation by satellite, the process is divided into steps. At first, satellite images are used to estimate the influence of clouds on the solar radiation. For a given location and for a same time, the darkest pixel in the month is assumed as giving the clear sky [11]. For the other days, the cloud reflectance is then calculated relying on the clear-sky day and the calculation is performed for all hours in the day. In this way, an effective cloud albedo can be calculated. To the next step, the theory of radiative transfer in the atmosphere will contribute a large part in the estimation of the solar radiation under clear sky condition, which also involves the critical presence of the data on three other elements: the quantity of aerosols in the air, the concentration of the water vapor and ozone. The total radiation is then calculated from the cloud albedo and the clear-sky irradiance.

2.4 LOA measurement

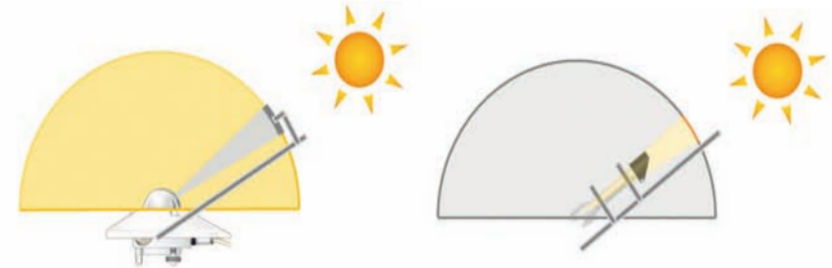


Figure 3: The CMP22 pyranometer and pyrheliometer CHP1 [3]

The experimental measurements are performed at the University of Lille campus located in Villeneuve-d'Ascq, France. The experimental procedure can be broken down into two key systems: the CMP22 pyranometer and pyrheliometer CHP1. The CMP22 pyranometer is designed for measuring the total irradiance (Watt/m²) on a plane surface. In addition, CMP22 uses very high quality quartz domes with wide spectral range (200 - 3600 nm) to estimate the total radiation. However, in this case we combined this pyranometer with an equipment named "shadower" that hides the sun and projects the shadow of it on the dome for estimating diffuse radiation only. On the other hand, the CHP1 pyrheliometer is the most commonly used to measure direct irradiance with high accuracy and reliability. Sunlight enters the instrument through a window and is directed onto a thermopile which converts heat to an electrical signal that can be recorded. The full viewing angle of CHP1 pyrheliometer is 5º, the slope angle is 1º, while the sun occupies a solid angle of 0.5º. The uncertainty of pyrheliometer CHP1 is around 2% for hourly data and 1% for daily data [12].

Chapter 3. Climatology of surface solar radiation at LOA's site

This chapter shows aspects of the climatology of surface solar radiation and its components over a year as measured at LOA's site at Villeneuve d'Ascq and the partition of direct and diffuse will be shown as well. The monthly transmittance and average monthly transmittance are illustrated respectively, then we compute the annual transmittance in this chapter. At LOA's data, we face with a difficulty of lacking data, thus, it is difficult to compute the total solar radiation at surface. Next, we try to correct in situ data for comparing solar radiation and its aspects to satellite data that is explained in next chapter.

3.1 Daily variation of solar radiation over a year

The annual daily variation of total, diffuse and direct radiation are described into fig.4 as a function of Julian days at Villeneuve d'Ascq in 2009. There is no significant difference of the variation of solar radiation from the period from 2009 to 2016. The energy of solar radiation is given in kWh/m^2. In term of total solar radiation, during summer the energy level of solar radiation reaches a peak from day 121 to day 213 and are more variable than at any other period of the year. In addition, we observed that the total solar radiation at the surface during winter period reaches the lowest level, was smaller than 3 kWh/m^2 then increase more than twice and reaches the peak of energy in the summer. This seasonal variation is expected because of the change of duration of daytime by season, especially at Villeneuve d'Ascq where the daytime in summer can be 16 hours at the maximum and decrease to 8 hours at winter. Furthermore, we have sharp time variation during this period. This variation can be explained by meteorological events such as the distribution of clouds.

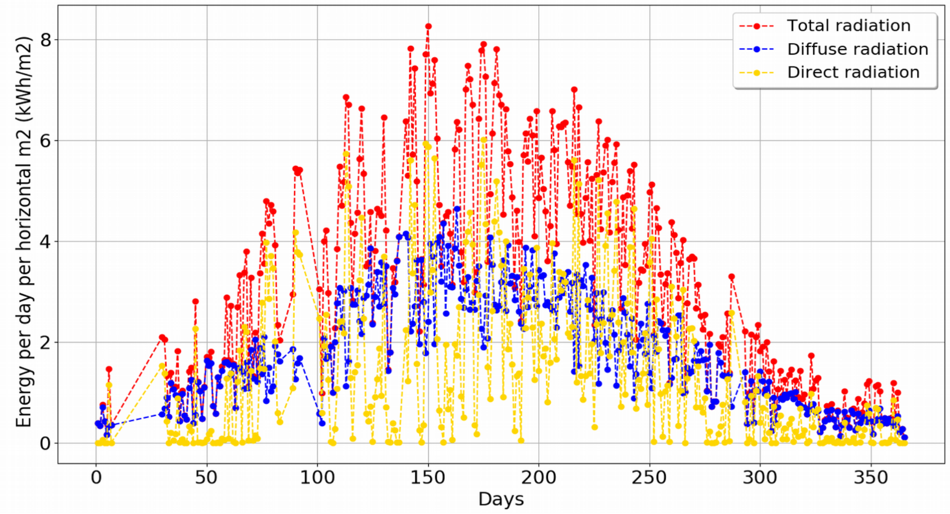


Figure 4: Variation of daily solar radiation in 2009

The distribution of clouds creates more effect on direct radiation than diffuse radiation. Furthermore, the level of direct radiation varied more significant and higher than the diffuse radiation. Therefore, at Villeneuve d'Ascq, the direct radiation has more effect on the variation of total irradiance than the diffuse radiation.

3.2 Partition between direct and diffuse radiation

The normalized histogram of solar radiance distribution for the data of LOA is shown in fig.5. The diffuse and direct solar radiation is drawn in the blue and yellow line respectively. We see that there are many days with low energy of direct radiation, thus, we ensure that these days are very cloudy. In contrast, we also see that there are many days where the energy is higher than 6kWh/m^2 as clean days.

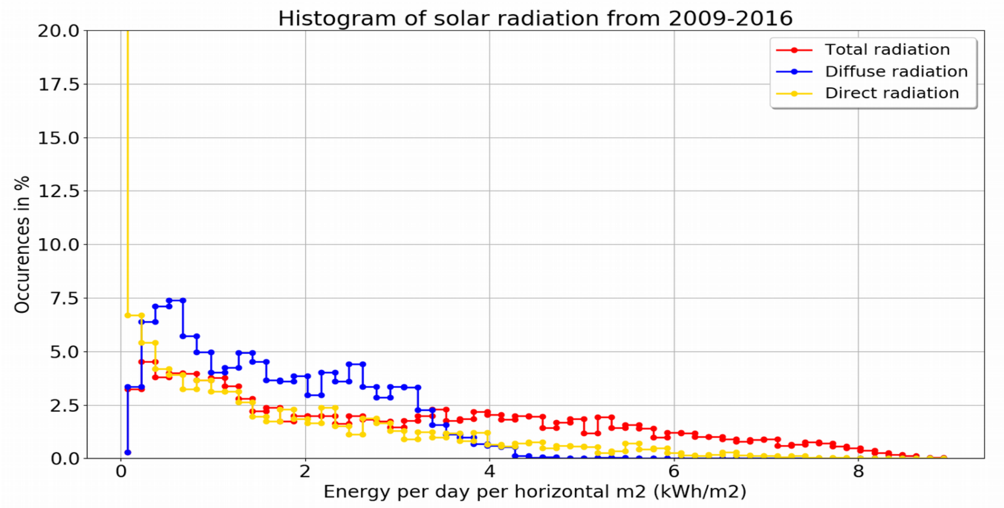


Figure 5: Histogram of daily solar radiation at Lille

The direct radiation over a year is computed and established in annex 4. In addition, the direct solar radiation recorded at LOA's site was around 500 kWh/m2 and accounts for approximately 45% ± 3 over the total solar radiation over one year at Lille. The energy of direct radiation during 8 years from 2009 to 2016 reach the highest value at 2015. In contrast, 2013 was recorded as the year where the energy of direct radiation is lowest. In general, there were no striking change of direct radiation through this period. On the other hand, the diffuse radiation given by LOA measurement accounts for 55% over the total solar radiation and its value was around 600 kWh/m2 over the period of 12 months.

3.3 Atmospheric transmittance

In this work the transmittance is estimated by monthly data and then yearly data for verifying its variation. The transmittance (T) is calculated following the ratio of the monthly solar radiation on horizontal surface (I) and the monthly extraterrestrial solar radiation (I_o).

$$T = \frac{I}{Io} x\,100\%$$

The total transmittance, from 2009 to 2016, fluctuated significantly by months between roughly 0.3 in the winter and approximately 0.6 in the summer which is shown fig.6a. Generally, the value of transmittance reached the highest value at April frequently, for example, at 2009, 2010, 2013 and 2015. In other years, the transmittance reaches a peak in July or September. In addition, the highest monthly value of transmittance was recorded at April of 2015, was 0.6 during the period of 8 years. In contrary, the lowest value was 0.25 in December of 2010.

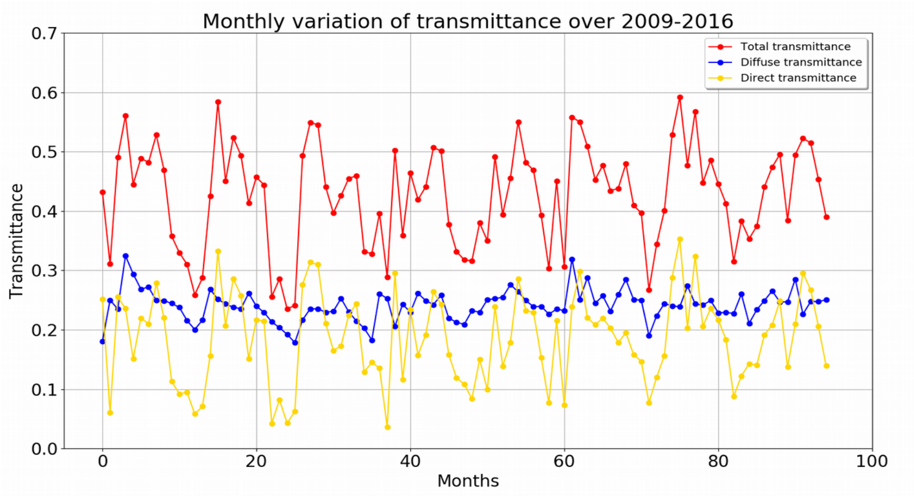


Figure 6a: The monthly variation of transmittance in each year from 2009 to 2016

Similarly the diffuse and direct transmittance show a fluctuation by season. While the direct transmission varies intensively during the period of 8 years, the range of variation of diffuse transmission change slightly over months. In general, the direct inradiance peaks on April of 2015, was approximately 0.35. On the other hand, the diffuse radiation reaches the highest level in April of 2009 which was roughly 0.32.

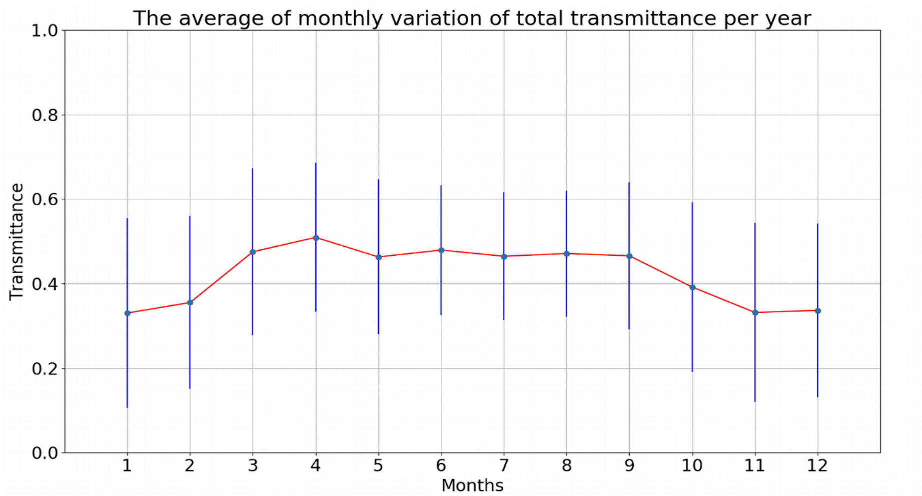


Figure 6b: The average transmittance per year

Furthermore, figure 6b indicates the average of monthly transmittance from 2009 to 2016. This value in winter time is lower than itself in summer time and the mean value of transmittance in one year was around 0.42 with a mean standard deviation of 0.18. The number of transmittance rises sharply in January and reaches the peak of 0.51 in April during this period. After that, it drops slightly in next month before fluctuates from June to September. Generally, there was a plateau of transmittance from March to September. After September, this trend levels off from November to January and stand at under 0.4. In addition, April is the month where the highest average value of transmittance has been observed. In term of direct and diffuse transmittance, they also reach the highest point of value at April. In term of direct transmittance, the highest monthly value was 0.23 while its lowest value was 0.12. In contrast, the diffuse transmittance did not vary a lot which was quite remained almost the same during a year. Although in July, we measured the highest energy level of solar radiation on the Earth's surface, the transmittance of solar radiation peaks in April. Therefore, the transmittance and the solar energy level are independent variable and unrelated to each other. The variation of transmittance can be explained by atmospheric condition at local area.

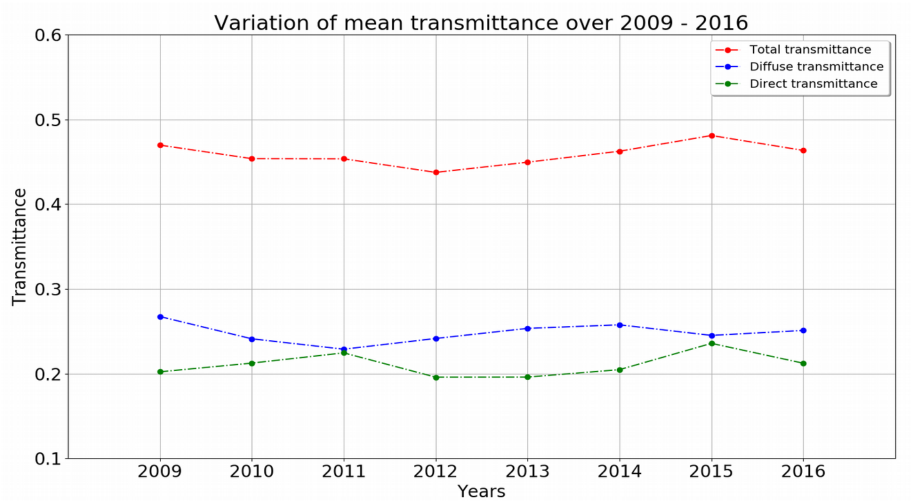


Figure 6c: The average transmittance in each year from 2009 to 2016

Figure 6c shows a fluctuation of transmittance in each year from 2009 to 2016. In contrast to monthly variation of transmittance, the yearly atmospheric transmittance changed slightly. Interestingly, we see that the average transmittance at Villeneuve d'Ascq was lower than the global average transmittance which is around 54%. It is observed that in the first year of the period, the total transmittance stood at 0.48 then continuously declined over the next 3 years to approximately 0.45 in 2012. After that, the total transmittance rises gradually and reaches the highest value at 2015 before dropping slightly in the last year. In term of diffuse and direct transmittance, they show an opposite trend through over the period from 2009 to 2016. The diffuse transmittance varies between 0.22 and 0.28 while the direct transmittance maintains at the same level around 0.2 during the period of 8 years.

3.4 Total solar radiation per year

A difficulty of accurate estimating the total energy of solar radiation per year comes from missing data because of technical reasons. For example in 2012 or 2016, the missing days can be a month or even more. Therefore, the value of total solar energy at the surface could be obvious less reliable. Hence, it required a corrected method for computing the total radiation on the Earth's surface during a year. For correcting the total radiation in one year, there are some ways to do it, but in this report, 2 solutions are used to correct the total solar radiation on surface. At first, the data will be corrected by year while the second way is to correct per month then make an addition.

The sum of total solar radiation is given in kWh/m2. During this period, the global of solar radiation on the Earth's surface was lower relatively than PVGIS data with the measurement uncertainty of 10 to 12% due to the missing days, for example in 2010 or 2012 [annex 4]. As we can see from fig.7, there was some differences in output data after calibration, we had seen better results when we compared the PVGIS data with two corrected method. However, with 2 corrected methods, the measurement uncertainty has decreased to lower 5% [annex 4]. Unfortunately, there are still no clues for proposing the best method for correcting the input data. However, during this work, we choose values from monthly corrected method because it is consistent with the trend given by PVGIS.

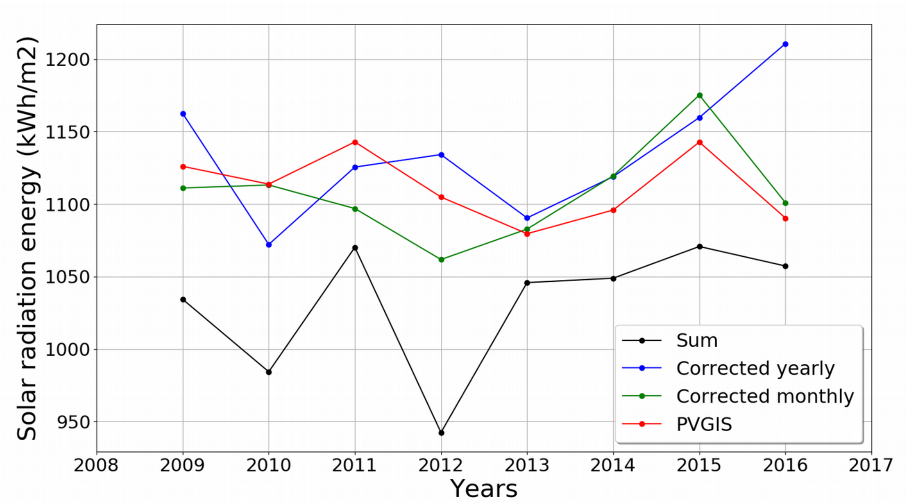


Figure 7: The comparison between corrected methods and PVGIS data

Chapter 4. Comparison between in situ data and satellite data

Comparisons will be performed to evaluate differences between two methods. The in situ measurement is assumed to give accurate results for the site, thus, our results can be used as a reference in the comparison. The comparisons will be at monthly, daily as well as hourly scales and concerns total radiation and its components. In this work, we are particularly interested in the evaluation of the direct and diffuse radiation by satellite.

4.1 Monthly average value

4.1.1 Total solar radiation

The results of the monthly total radiation calculations of PVGIS and LOA estimation are shown in figure 8a presented into red and blue line respectively. But the variation of solar radiation from both are quite close in general especially in winter time. We can see although there are some difference between two methods and these differences are shown sometimes in winter, however, it is clear in summer time. The level of the total radiation between PVGIS and LOA is lower than 5%. The mean bias difference (MBD) of total solar radiation is 0.36 kWh/m^2 which means PVGIS tends to overestimate the total radiation. In addition, the root mean square difference (RMSD) is 4.6 kWh/m^2.

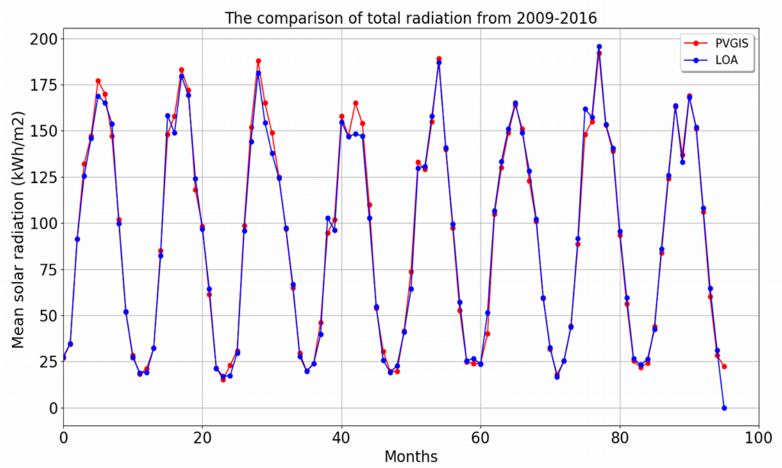


Figure 8a: The comparison of total solar radiation

During this period, PVGIS gave clear overestimated values at summer time from 2009 to 2012. However, in the last 4 years of the period, there are almost no differences between two estimations in term of total radiation. This requires more comparisons of diffuse and direct radiation from both estimation to make a more detailed evaluation of which component leads to the difference of the total radiation.

4.1.2 Direct solar radiation

The figure 8b shows how direct solar radiation varies regarding to PVGIS data and the ground measurement is done by LOA. And in this figure, we start to see a clearer discrepancy between two methods. The level of the difference between PVGIS and LOA of direct radiation measured between LOA and PVGIS is up to 5-10% while the MBD is 1.61 kWh/m^2. It means that PVGIS also tends to make an overestimation of direct radiation, while the RMSD is 7 kWh/m^2. These differences are observed mainly in summer time especially in July where the energy of irradiance reaches a peak. Because of this reason, in next sections, summer time will be chosen for looking deeper in term of daily and hourly data. Besides this, in this case we also see some months, direct radiation was underestimated by PVGIS.

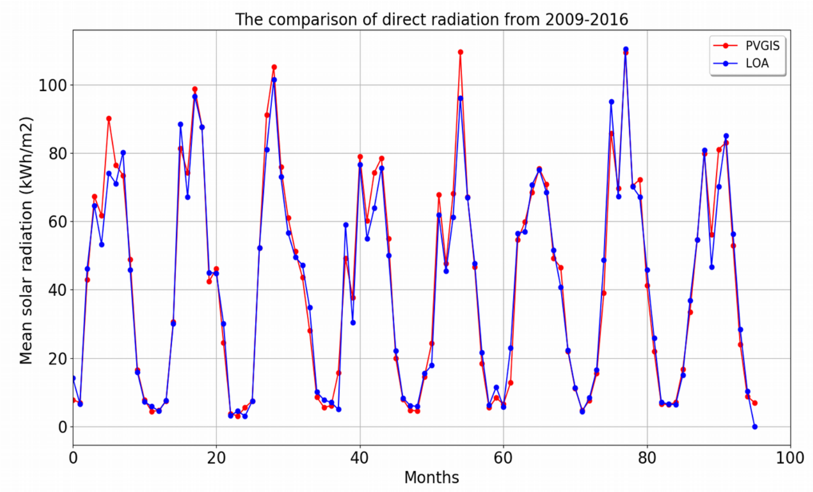


Figure 8b: The comparison of direct radiation

As we mentioned in section 4.3.1, PVGIS and LOA's measurements gave many close results in term of total radiation, for example in July of 2014 and 2016. However, in these months, direct radiation is overestimated by PVGIS. Thus, there is a presumption that diffuse radiation will be underestimated in these periods. Then we need to do a similar comparison with diffuse radiation.

4.1.3 Diffuse solar radiation

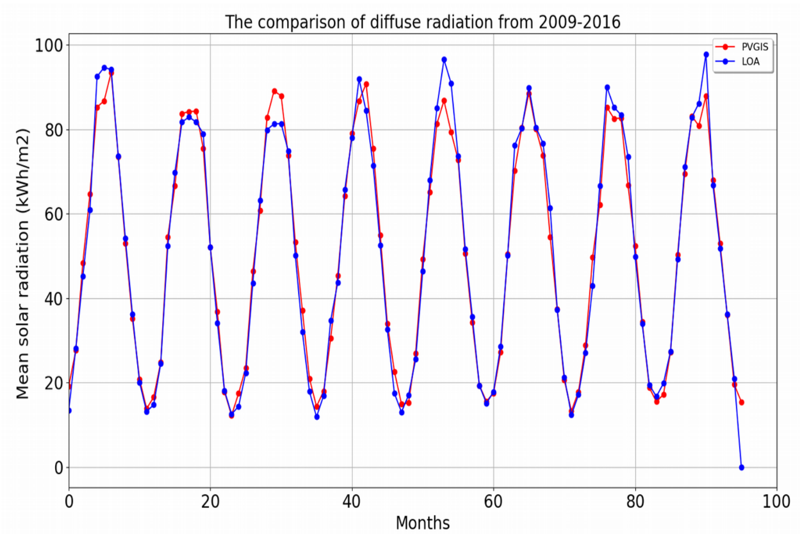


Figure 8c: The comparison of diffuse radiation

Comparing to the data of LOA, the accuracy of the estimation of diffuse radiation given by PVGIS is less than 5 % and its MBD is - 0.24 kWh/m^2. Therefore, it proves that our presumption is correct. RMSD is 3.6 kWh/m^2 Furthermore, we can see from fig.8c that the diffuse solar radiation is generally underestimated except in 2010 and 2011 where the diffuse radiation is surprisingly overestimated. In 2013 , 2015 and 2016, it is clear that PVGIS underestimates the diffuse radiation. Again, the difference is larger in summer time and lower in winter. These could be explained by the variation of climatic conditions in summer.

To summarize, PVGIS and LOA measurement show relatively close monthly values. In addition, they provided relatively quite close values of total irradiance. In general, diffuse and direct estimations tend to be overestimated or underestimated respectively. However, these trends are not totally true because there are few months where an inverse trend has been shown. For deeper-understanding how difference they are, we will use daily average values between LOA and PVGIS data for next comparison. Therefore, we chose days from July of 2013, 2014 and 2016 for evaluating daily data in next section because the total radiation given by both methods are close while its components are different for these years.

4.2. Daily average values

As we said in 4.1.3, we will look at daily values of solar energy in July of 2013, 2014 and 2016. Regarding daily data, PVGIS and LOA give surprisingly a similar result for total radiation [annex 1]. Although in some days the daily total radiation is still overestimated or underestimated. However, there are a huge difference between PVGIS and LOA‘s estimation when we go into the diffuse and direct radiation.

During these years, both methods gave results which are the most similar in term of beam and diffuse radiation in July of 2014 where the measurement uncertainties are 3.1 kWh/m2 and 0.9 kWh/m2 respectively [annex 2]. In 2013 and 2016, the estimation of diffuse and direct radiation from PVGIS and LOA data had significant differences.

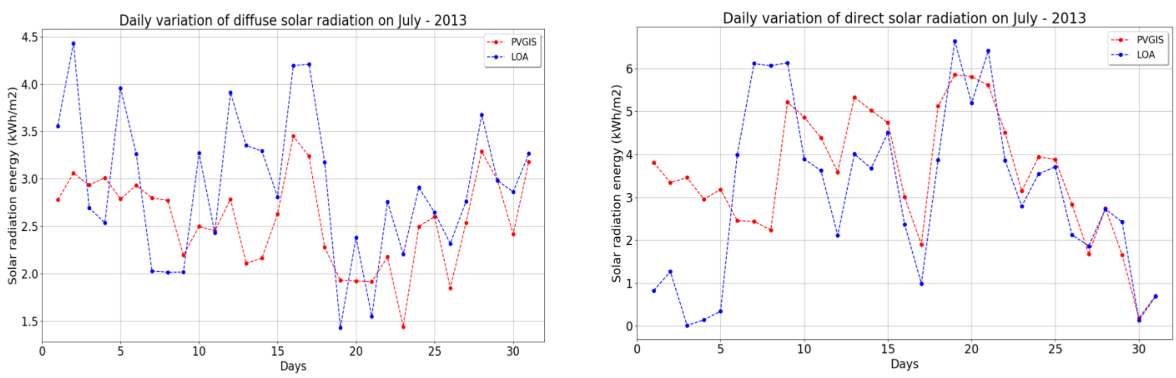


Figure 9: The daily variation of (a) diffuse and (b) direct solar radiation on July - 2013

At 2013, there is a dramatic discrepancy in the result of diffuse and direct radiation between PVGIS and LOA's estimation in the first ten days (fig.9). According to the climatic record and sky imager application from LOA, there was a raining period with thick clouds from day 1 to day 5, though, the value of direct radiation, which is given by PVGIS, was high. In addition, the sky was clean in day 7 and day 8, the measured values of direct radiation by PVGIS was even lower than the value of previous cloudy days. Obviously, during the first 10 days of the period, PVGIS seems do not work well. After that, PVGIS started to work better in next days and the level of beam radiation tends to be overestimated, while diffuse radiation tends to be underestimated. Besides this, during few days where we observed high energy of direct radiation, there is an opposite trend where PVGIS overestimates diffuse and underestimates direct aspect.

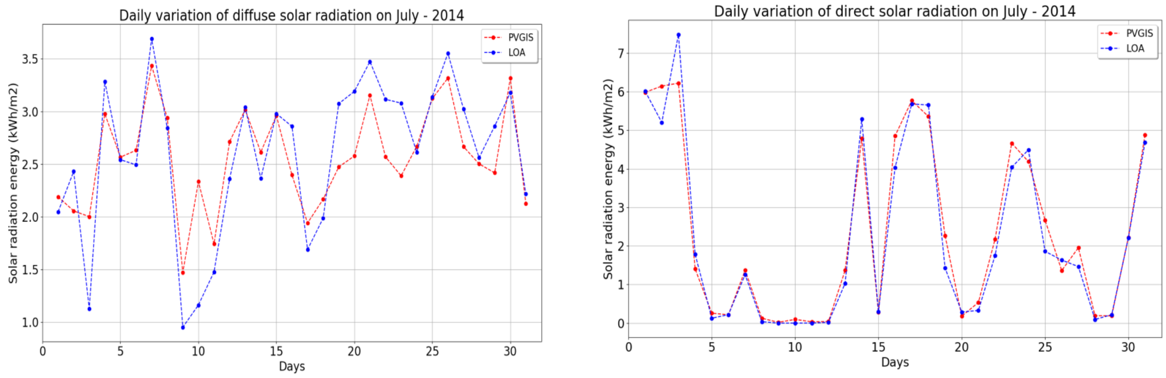


Figure 10: The daily variation of (a) diffuse and (b) direct solar radiation on July - 2014

Next, on July of 2014 and 2016, we did not have a considerable discrepancy as in 2013, but there are still differences especially for diffuse radiation (Fig.10a and Fig.11a). Surprisingly, PVGIS and LOA gave relatively close results (Fig.10b) in term of direct radiation during July 2014. In general, in 2014, PVGIS continues to overestimate direct radiation and underestimate diffuse radiation but in some cases especially at sunny days, PVGIS shows an inverse result.

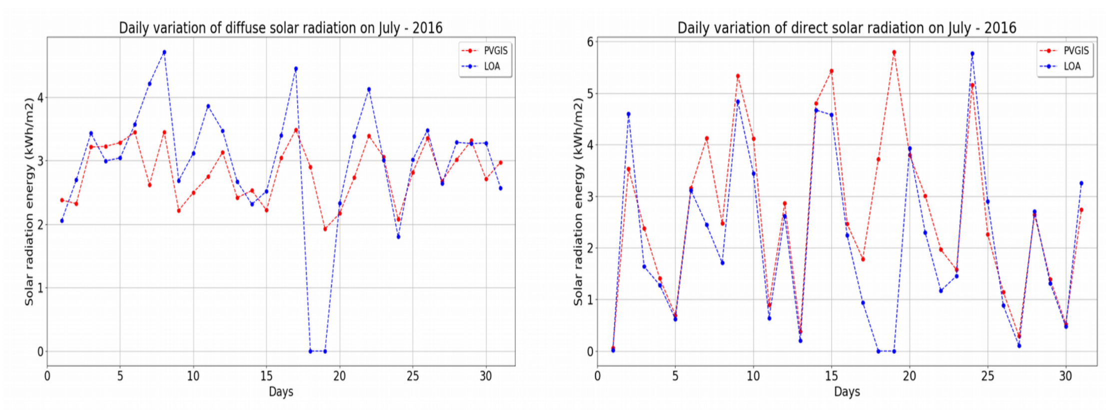


Figure 11: The daily variation of (a) diffuse and (b) direct solar radiation on July – 2016

In 2016, we do not have any results for the 18th and 19th due to technical problems at LOA's site. Similar to 2013 and 2014, there are no significant change in 2016 where direct radiation is generally overestimated and the diffuse is underestimated comparing to LOA's estimation (fig.11a and b). Similar to 2013 and 2014, we observed an inverse trend in few days where the direct given by PVGIS is underestimated and the diffuse one is overestimated. According to the above plots and using sky imager application, this trend appears in pristine days or days where the sky is clear most of the day.

During this year, we see two interesting days which are day 7th and day 20th where their total radiations are quite close [annex 1]. However, while PVGIS and LOA tend to give close values for both direct and diffuse radiation on day 20, they give very different values on day 7. Therefore, we will make comparisons in term of hourly data for understanding the reasons that lead to PVGIS's errors.

4.3. Hourly average value

In this comparison, we have chosen day 07th and day 20th of July where they are partly cloudy days [annex 5]. The weather condition was more complex on day 20th. In this morning, the sky was cloudy with different kinds of clouds in the atmosphere. In this moment, diffuse radiation was overestimated by PVGIS while there is almost no difference between PVGIS and LOA's estimation in term of direct radiation. In the afternoon, we had less clouds and the sky became clear. PGVIS has a tendency to create inverse errors where they show an underestimation of diffuse radiation and an changing bias for direct radiation. As a result, both direct and diffuse energy are correctly estimated by PVGIS.

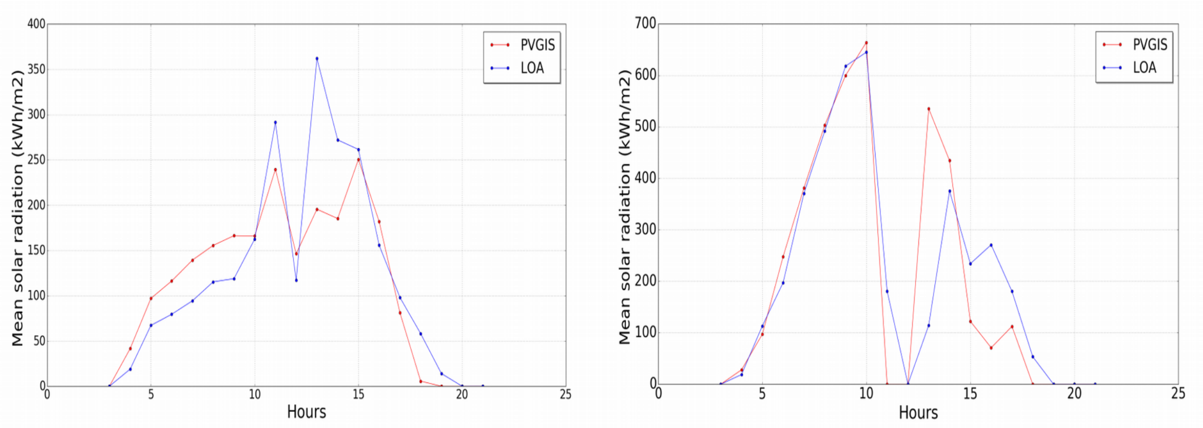


Figure 13: The hourly variation of (a) diffuse and (b) direct solar radiation at day 20

On day 07th, the value of direct radiation given by PVGIS is overestimated while its diffuse radiation tend to be underestimated (fig.14). Through sky imager application [annex 5], the distribution of cloud is the only difference between day 07 and day 20 of July, 2016 . On day 07, we observed that the sky was partly cloudy all day while the sky was only cloudy in the afternoon of day 20. From these, we see that the distribution and type of clouds have an huge impact on the accuracy of estimating solar radiation of PVGIS.

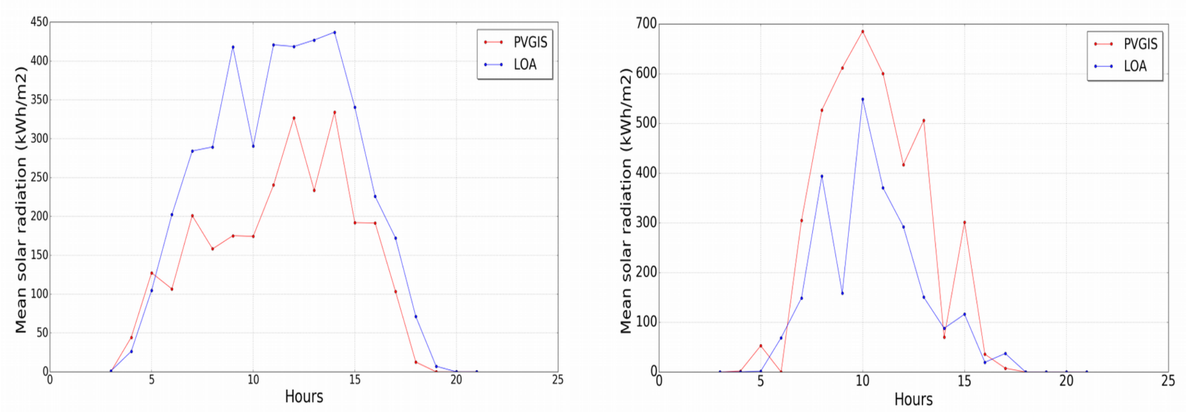


Figure 14: The hourly variation of (a) diffuse and (b) direct solar radiation at day 07

4.4 Synthesis and discussion

With monthly, daily, and hourly data, we have analyzed that the bias between PVGIS and LOA is different in signal and amplitude. In order to analyze further statistically the bias, we defined three kind of classifications that correspond to clear days, partly cloud days and very cloudy days. Based on the ratio between direct radiation over total radiation by LOA's site, these classifications have been defined by ratio direct/total ≥ 0.7, 0.3 < ratio direct/total < 0.7, and ratio direct/total ≤ 0.3 respectively. These classifications have been defined empirically from the study of daily data. The mean bias differences of direct and diffuse radiation between PVGIS and LOA at sunny days are -0.6 and 0.3 kWh/m^2 respectively. It means that in this case, PVGIS tends to make an underestimation of direct radiation and overestimation of diffuse radiation. For partly cloudy days the MBD are 0.015 and – 0.13 kWh/m^2 which means that PVGIS underestimates diffuse and overestimates direct radiation at partly. For very cloudy days, PVGIS make a same mistake as at partly cloudy days and its mean bias differences for direct and diffuse radiation are respectively 0.13 and - 0.08 kWh/m^2.

Furthermore, according to the daily variation of atmospheric transmittance at Villeneuve d'Ascq, their values are normally lower or equal to 0.8, however, sometimes transmittance can reach higher value due to 3D cloud effect. During these periods, the energy of direct radiation is high and clouds add diffuse component to the radiation, then we have an addition of direct anh diffuse radiation at the surface. As a result, atmospheric transmittance can be higher than 0.8 at certain time. Then we make an calculation of differences of solar radiation between PVGIS and LOA's measurement as the function of transmittance > 0.8 which we named as "3D_effect" from 2013 to 2016. If we consider day 07 and day 20 in July of 2016, we decided to analyze the sensitivity between PVGIS and LOA bias and the increase of "3D_effect". Corresponding to each day, the minutes of "3D_effect" at day 07 and day 20 are 140 and 13 respectively. This effect might be the reason that explains the bias difference between the two days.

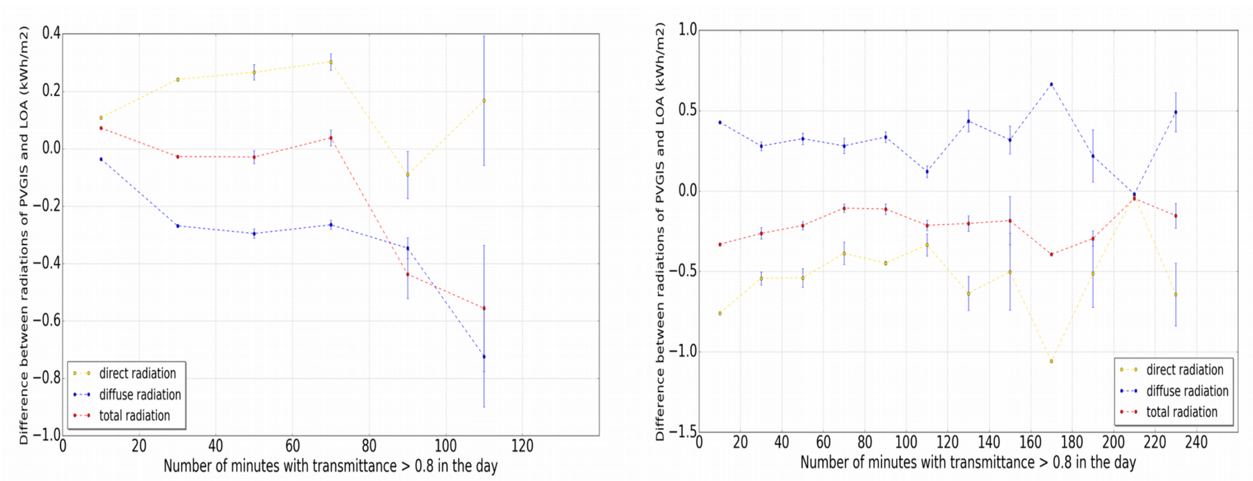


Figure 15: Mean bias difference as the function of transmittance > 0.8 at (a) very cloudy days (b) sunny days

According to these figures, it is clear that in sunny days (fig.15b), PVGIS tends to overestimate diffuse radiation and underestimate the direct radiation in general. This is relevant with what we mentioned above that we observed this trend in days with high amount of direct radiation. Furthermore, the mean bias difference of total radiation are close to 0 which means that PVGIS give a good estimation of total radiation. Therefore, there is a compensation between direct and diffuse radiation. In addition, PVGIS tends to create errors without "3D_effect", however, there is no significant impacts of "3D_effect" on PVGIS's errors when it increases because the energy of solar radiation is high in sunny days. The bias can be explained by impacts of scattering aerosols on modelling of PVGIS [5].

In term of very cloudy days (fig.15a), it has been shows that PVGIS tends to give an inverse trend comparing to the case of sunny day. In this case, PVGIS overestimates the direct radiation and underestimates diffuse radiation with and without "3D_effect". The mean bias difference of total radiation is close to 0. Again, PVGIS shows a compensation between direct and diffuse radiation. Interestingly, we see that "3D-effect" has an impact on PVGIS's work. Fig.15a shows that when the longer period of "3D_effect" , the mean bias difference of direct and diffuse radiation are increased. It means that "3d_effect" can be a reason that makes PVGIS work incorrectly.

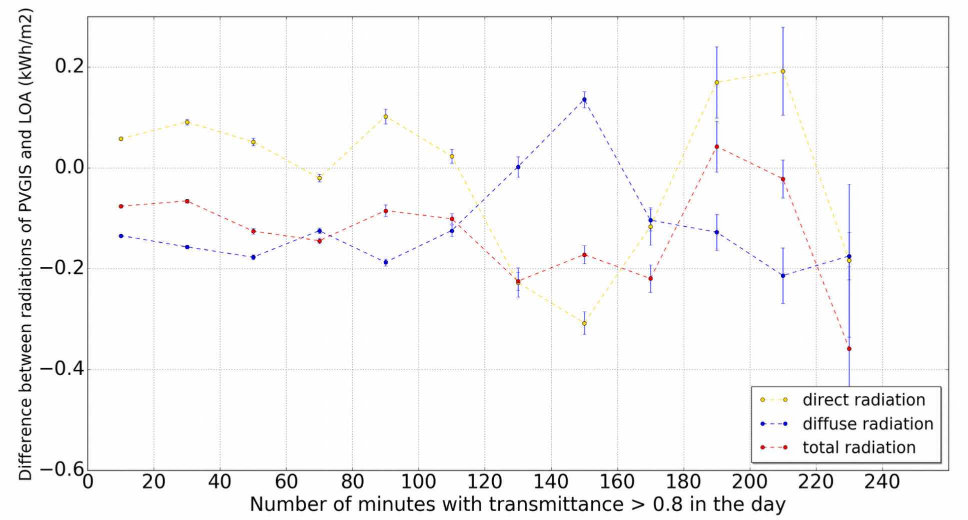


Figure 15: Mean bias difference as the function of transmissivity > 0.8 at (c) partly cloudy days

For partly cloudy days, the weather is more complex than the other classification. The sky can be cloudy all day or cloudy in the morning and then suddenly change. Similar to very cloudy day, PVGIS tends to overestimate direct radiation and underestimate diffuse radiation in this case (fig.12c). And PVGIS still give a good estimation of total radiation because its mean bias difference of total radiation is close to 0, thus, there is an compensation between direct and diffuse radiations. In general, PVGIS seems to make a same mistake as it does in very cloudy day. PVGIS still make errors in estimating direct and diffuse radiation without "3D-effect". Although there are no strong clues to prove that with an increase of "3D_effect", PVGIS seems to makes more mistakes in this case. However, we can see (fig.15c) the mean bias differences of total radiation tend to increase along with the increase of "3D_effect" period.

So this effect can be used to explain the difference of radiation between PVGIS and LOA data on day 07 and day 20 of July, 2016. Because the sky of day 07 was cloudy all day, thus, the period of "3D_effect" is longer than on day 20 where the sky was only cloudy in the morning. From that, PVGIS tends to create more errors in estimating radiation at the surface on day 07.

To summarize, it has been shown that there are bias of monthly, daily and hourly data between PVGIS's and LOA's measurement regarding to direct and diffuse radiation. For very cloudy and partly cloudy days, these bisas can be explained by "3D-effect". However, we also see that there is a symmetric bias between PVGIS and LOA without affection of "3D_effect". This bias can be explained by the relation between reflectance and optical thickness of the cloud measured by satellite due to non-linear relation.

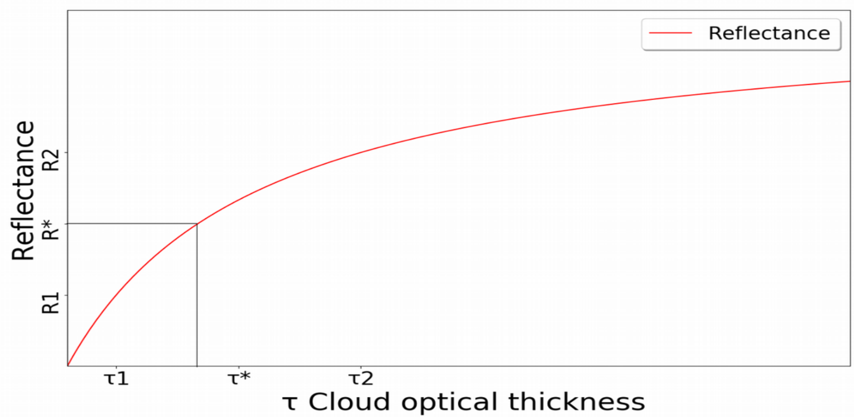


Figure 16: The relation of reflectance and atmospheric optical depth

From fig.16, we can see that the optical thickness can be retrieved from the reflectance. Because clouds in the atmosphere are inhomogeneous and satellite spatial resolution is limited so the estimation of optical thickness from reflectance is symmetrically underestimated. For example, R1 to R2 is assumed as the range of the reflectance of cloud, we can compute a mean value R*. From these values, we can compute the corresponding atmospheric optical depth τ_1 and τ_2. The problem is that the mean value of reflectance is not consistent with the real value of optical thickness τ*. Therefore, the optical depth τ given by the mean reflectance has been underestimated.

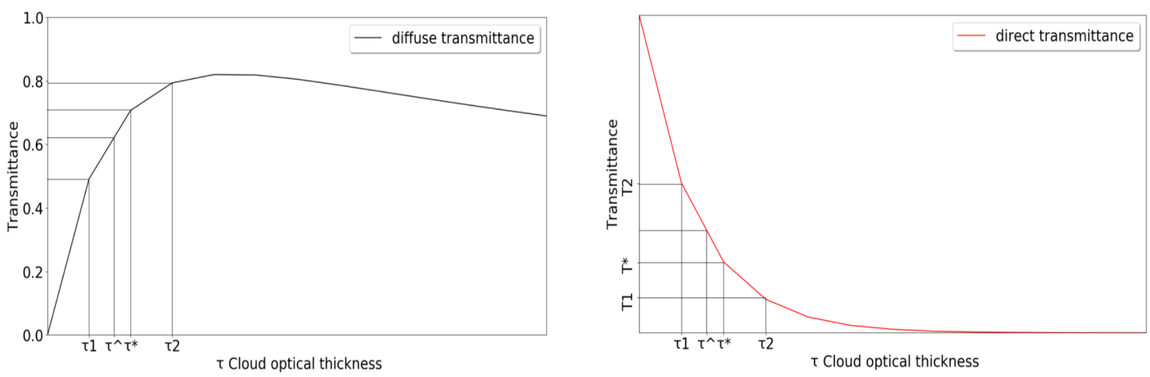


Figure 17: The relation of atmospheric optical depth and diffuse (a) and direct (b) transmittance, τ^: the real mean optical depth`

Then from optical thickness, we can estimate the direct and diffuse radiation. Because the optical thickness retrieved from the reflectance of cloud is incorrect, the estimation of direct or diffuse transmittance may be not accuracy. This problem is relevant with our comparison in term of direct radiation where we see that the value of direct radiation from PVGIS is higher than LOA's estimation. In contrast, diffuse radiation will be underestimated and it is consistent with our comparison where PVGIS's estimation tends to give lower results than LOA's estimation.

Chapter 4. Conclusion

This work concerns the study of total radiation and its components at the surface in Villeneuve d'Ascq. The aim is to analyze the climatology of the surface radiation anh to evaluate the accuracy of satellite's estimation of global radiation given by PVGIS website.

In Villeneuve d'Ascq, the partition of diffuse radiation is higher than the direct aspect which account for 55% over the total radiation. In addition, the annual atmospheric transmittance at Villeneuve d'Ascq is lower than the global transmittance. In term of monthly average transmittance, it reaches a highest value in April during a year and the monthly transmittace of the period from 2009 to 2016 varies between 0.25 and 0.6.

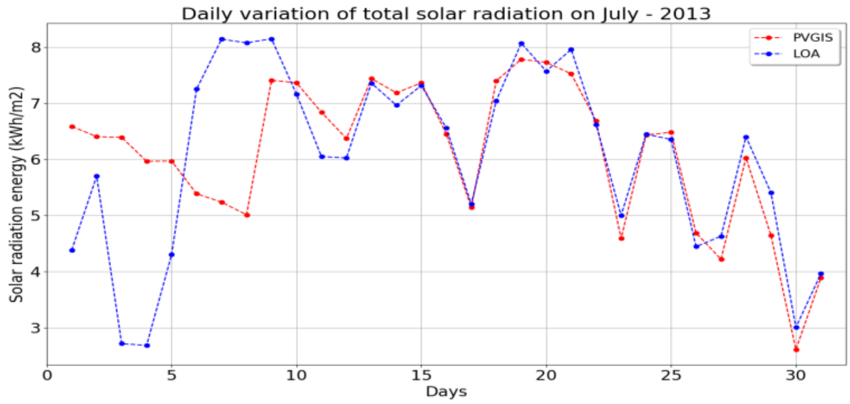
At the monthly scale, total radiation from LOA and PVGIS are in relatively good agreement. However, this good agreement results often in the summer from a compensation between a positive biasfor direct radiation and a negative bias for diffuse radiation. In term of direct radiation, the mean bias difference of PVGIS is 7 kWh/m^2. This bias of diffuse and total radiation are respectively 3.6 and 4.6 kWh/m^2.

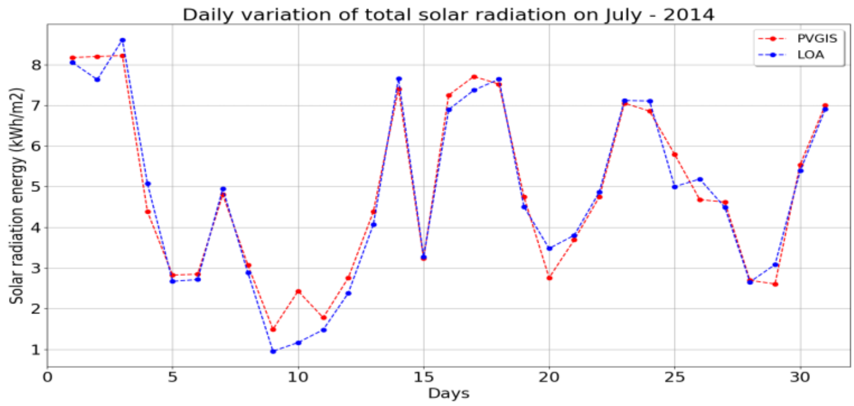
However, the errors of PVGIS's estimation regarding to daily data is more complicated. At sunny days, it has been shown clearly that direct radiation tends to be underestimated by PGVIS while diffuse aspect is overestimated comparing to LOA's estimation. It might be due to impacts of scattering aerosols that would be overestimated with the modeling of PVGIS. In addition, in the case of very sunny day, LOA pyrheliometer might overestimate beam radiation because of circumsolar radiation (forward radiation just around the Sun disk). While the modelling does not account for circumsolar radiation. At very cloudy day, PVGIS tends to give an inverse trend. At partly cloudy days, this is the most complex case in three categories and PVGIS underestimates diffuse radiation and overestimates direct radiation generally.

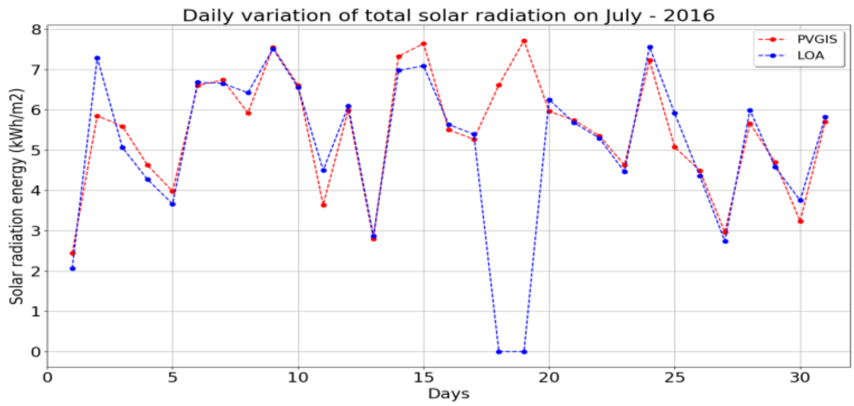
Regarding to hourly scale, the sudden change of weather especially the distribution of cloud along with the increase of "3D_effect" shows an impact of estimating solar radiation by PVGIS at partly and very cloudy days. Therefore, the extinction of "3D_effect" has been proven to affect the bias between PVGIS and LOA measurement. Besides this, at cloudy days the spatial resolution of satellite can miscalculate the atmospheric optical depth from the reflectance which then results to the incorrect estimation of direct and diffuse radiation at the surface

For further research, we want to explain clearer the reasons that make PVGIS work incorrectly at the case of partly cloudy days. On the other hand, we can use Lidar for classifying types of cloud and estimating the respective atmospheric transmission of each cloud.

Annex 1: The daily variation of total radiation at 2013, 2014 and 2016







Annex 2: The monthly energy of direct and diffuse given by PVGIS and LOA

Time	Beam radiation_PVGIS (kWh/m2)	Beam radiation_LOA (kWh/m2)	Diffuse radiation_PVGIS (kWh/m2)	Diffuse radiation_LOA (kWh/m2)
7/2013	109.61	96.08	79.65	90.92
7/2014	71.78	68.59	79.43	80.39
7/2016	72.39	65.83	82.54	91.42

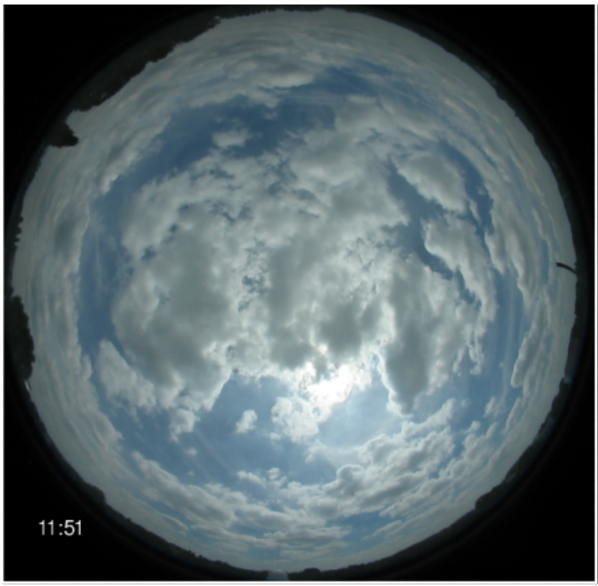
Annex 3: The total radiation with and without correcting

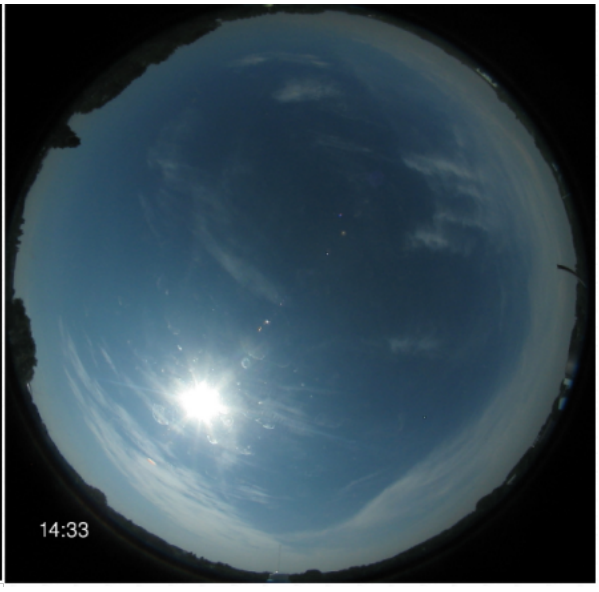
Year	Total solar radiation without corrected (kWh/m2) (a)	Yearly corrected total solar radiation (kWh/m2) (b)	Monthly corrected total solar radiation (kWh/m2) (c)	PVGIS (kWh/m2)	Observed days
2009	1034.38	1162.56	1111.13	1126.1	325
2010	984.35	1072.17	1113.21	1113.8	335
2011	1070.21	1125.56	1096.97	1142.9	347
2012	942.47	1134.18	1061.79	1104.9	303
2013	1045.86	1090.48	1082.77	1079.6	350
2014	1048.91	1118.96	1119.51	1095.9	341
2015	1070.78	1159.72	1175.25	1142.8	337
2016	1057.31	1210.72	1101.03	1112.8	319

Annex 4: The energy of direct radiation per year

Year	Sum of direct solar radiation (kWh/m2)	% Direct
2009	497.25	42.8
2010	487.87	45.4
2011	542.56	48.1
2012	496.78	43.7
2013	463.46	42.5
2014	484.73	43.3
2015	554.09	47.8
2016	543.83	44.9

Annex 5: The sky image on day 07 and day 20 of July, 2016





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